Application-Specific Heat Pipe Design and Performance Considerations

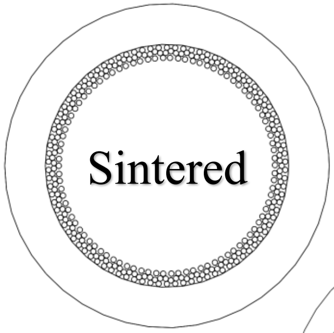
Jesse Maxwell
Timothy Holman
US Naval Research Laboratory

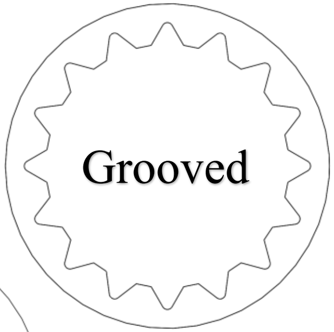
THERMAL & FLUIDS ANALYSIS WORKSHOP
GSFC · 2015

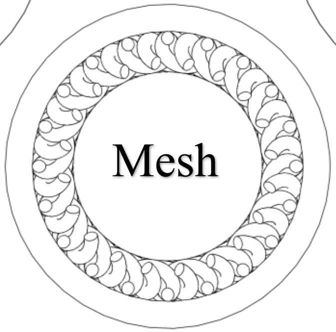
Abstract

A theoretical model is developed for quasi-one-dimensional constant conductance heat pipes (CCHP) with non-Darcian wicks in steady state and solved numerically with state-dependent working fluid properties across operational temperature for various parameters. It is demonstrated that preferential configurations exist for maximizing heat transfer capability or minimizing temperature gradients overall or in consideration of design or manufacturing constraints.

Heat Pipe





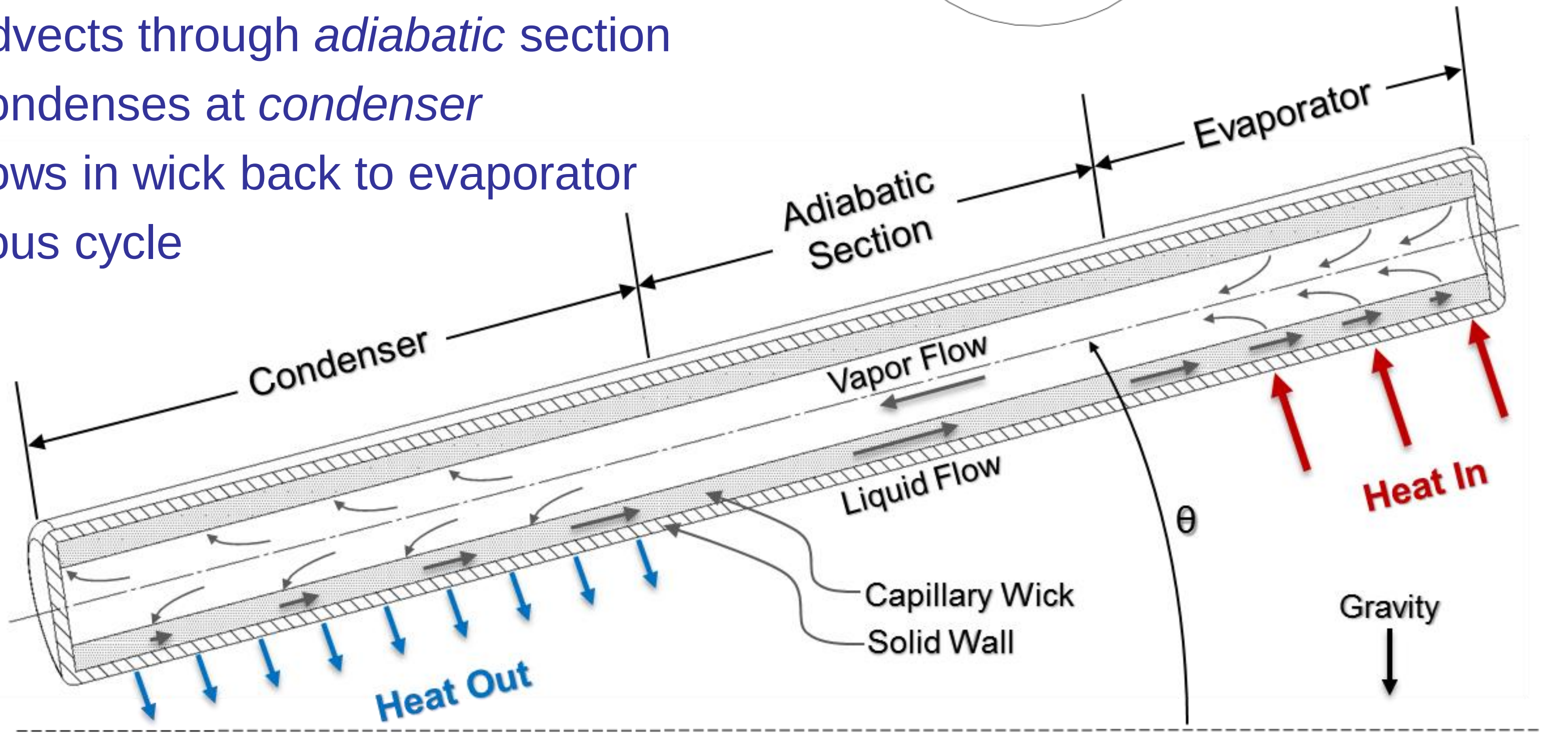


Features

- Sealed container
- Working fluid, liquid & vapor phases
- Saturated capillary wick

Principle of Operation

- Liquid evaporates at *evaporator*
- Vapor advects through *adiabatic* section
- Vapor condenses at *condenser*
- Liquid flows in wick back to evaporator
- Continuous cycle



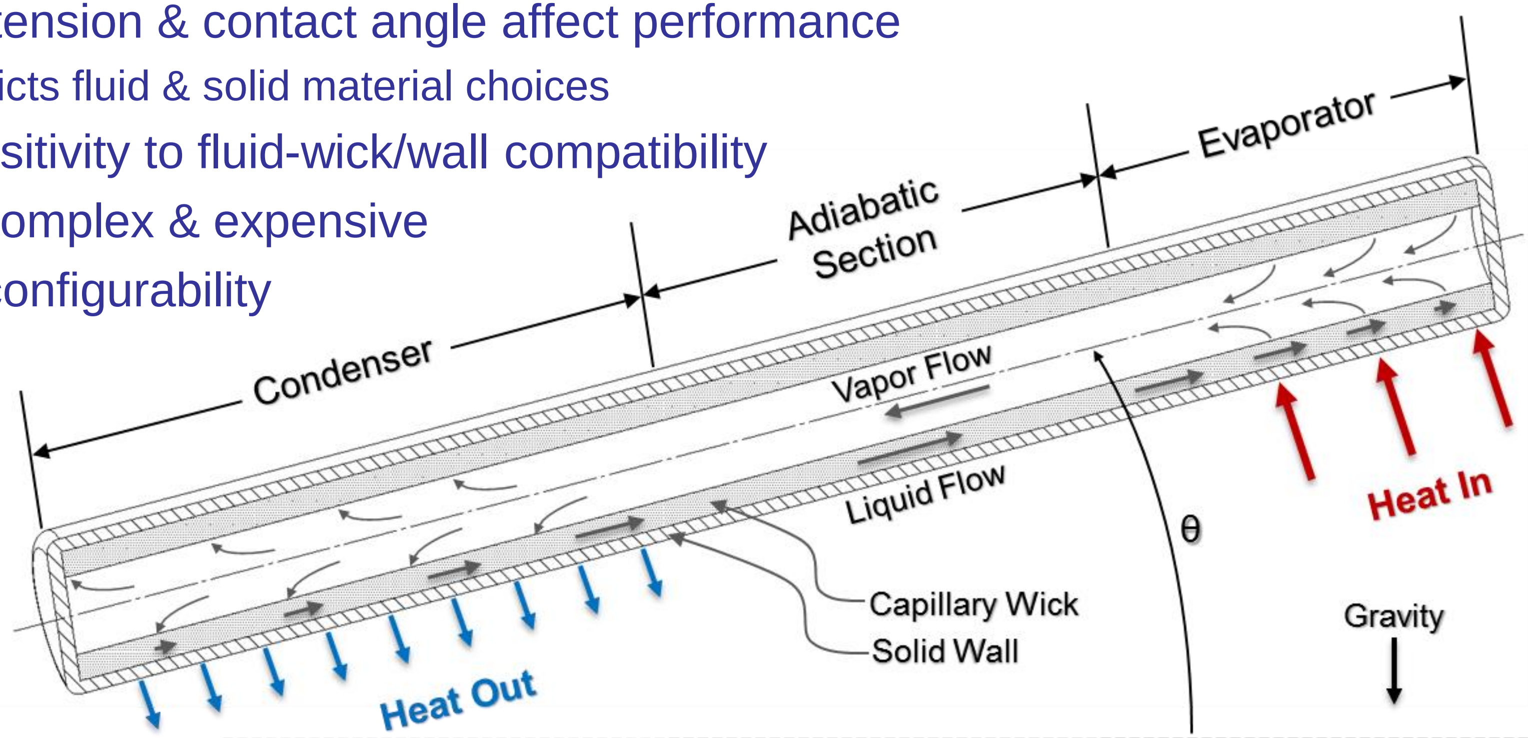
Heat Pipe

Advantages

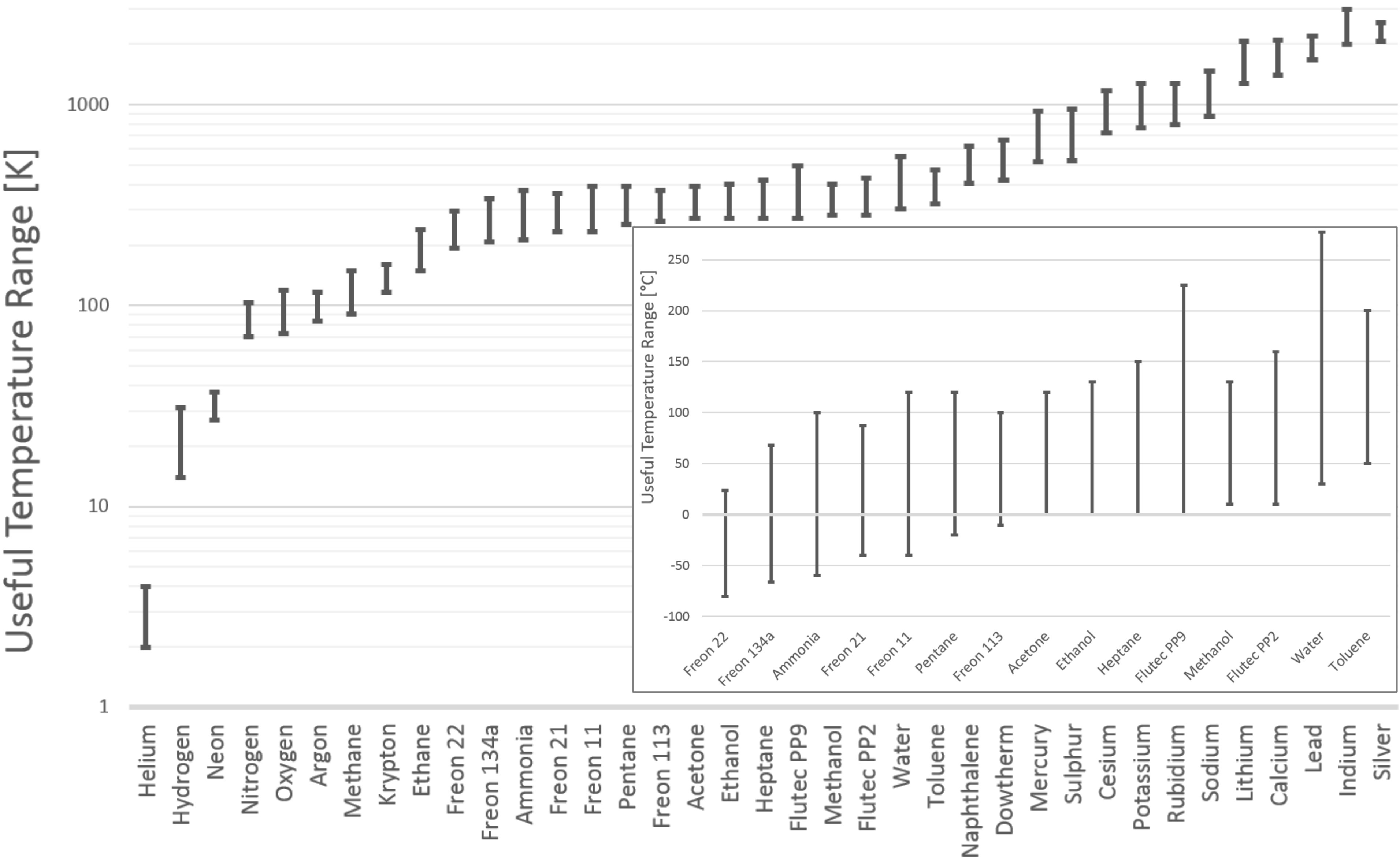
- Operates with or against gravity, or micro-g
- Can approach 10^1-10^4x the thermal conductivity of solid Copper
- No moving mechanical parts → high reliability

Disadvantages

- Limited operational temperature range
- Surface tension & contact angle affect performance
  - Restricts fluid & solid material choices
- High sensitivity to fluid-wick/wall compatibility
- Wick is complex & expensive
- Limited configurability



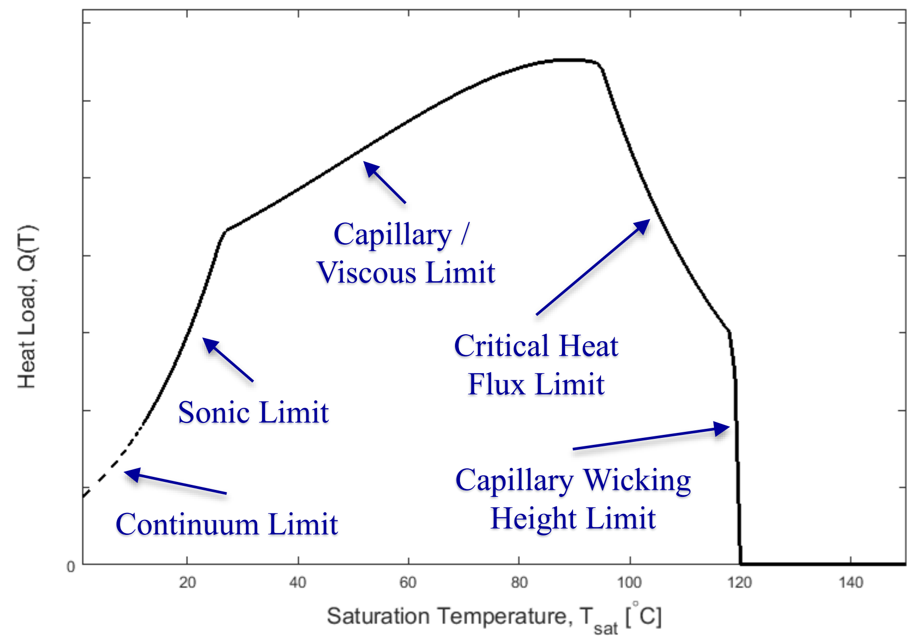
Working Fluids



Performance Limitations

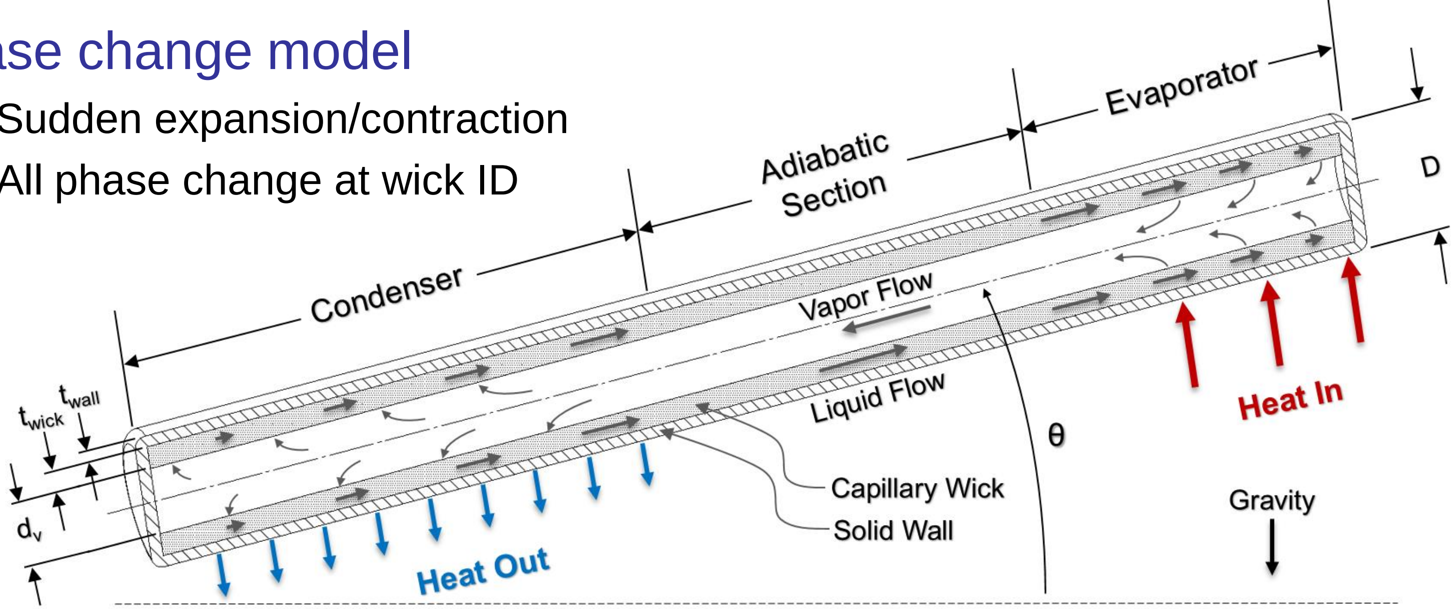
Design- and Fluid-Dependent Limitations

- Continuum Limit
  - Vapor molecules too sparse & liquid resistance too high
- Sonic Limit
  - Vapor flow approaches speed of sound
- Capillary Limits: Viscous, Wicking Height
  - Capillary forces balanced by fluid pressure drop
  - Capillary forces insufficient to overcome gravity
- Critical Heat Flux / Boiling Limit
  - Heat flux vaporizes liquid in wick faster than can be replenished, causing wick dry-out
- Entrainment Limit
  - Vapor traveling to condenser entrains counter-flowing liquid returning to evaporator
- Freezing & Critical Temperature Limits
  - Liquid must be present for capillary action
  - Latent heat decreases to zero as the liquid-vapor critical point is approached
- Temporal Limit
  - Rapid heat flux occurs too quickly for evaporation, vapor flow, condensation and environmental rejection to sufficiently occur



System Model

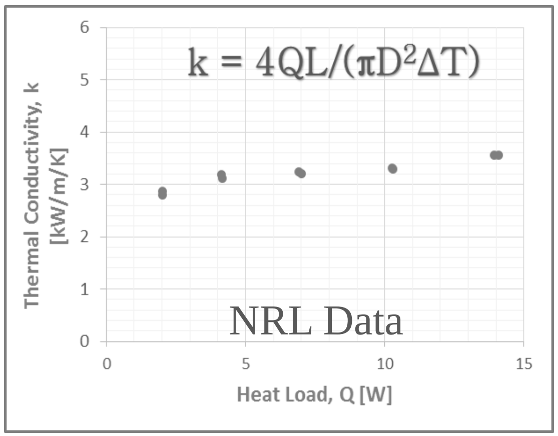
- Quasi-one-dimensional
  - Radially symmetric
  - Large aspect ratio
- Constant, uniform heat fluxes
- Wick model
  - Homogeneous, an/isotropic structure
    - Separate radial & axial porosity
  - Inlet/outlet pressure drop
  - Perfect volume saturation
- Phase change model
  - Sudden expansion/contraction
  - All phase change at wick ID
- Case model
  - Homogeneous solid
  - Radial heat conduction
  - Contact conductance
- Fluid model
  - Radially symmetric, quasi-1D
  - State-dependent properties
  - Capillary action & viscous flow through uniform, round channels

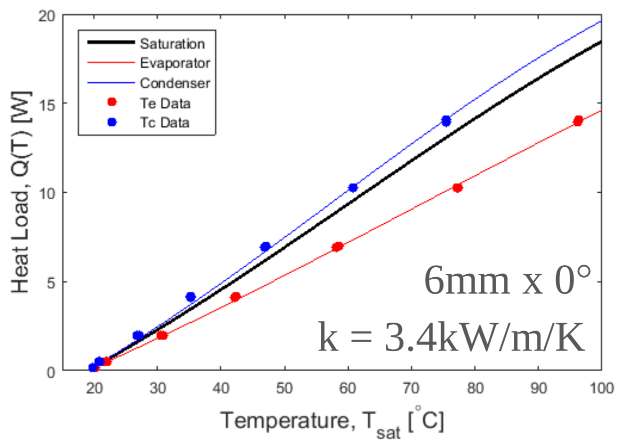


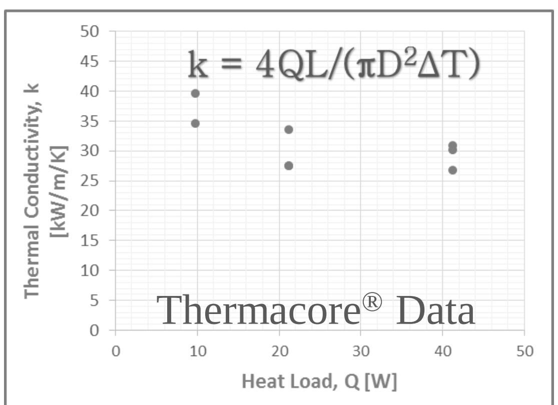
Preliminary Verification

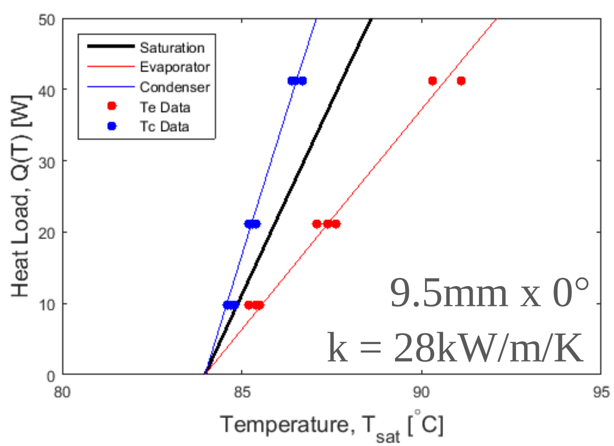
Q(T) – off-the-shelf Cu-H_2O heat pipes

- *OD* x *tilt angle*
- 150mm L, 25mm L_E, 50mm L_C, 5% ID wick thickness
  - Except bottom left & center plots: 8” L, 2” L_C, 1.3” L_E
- Sintered Cu wick, 30µm pore size, 60% porosity

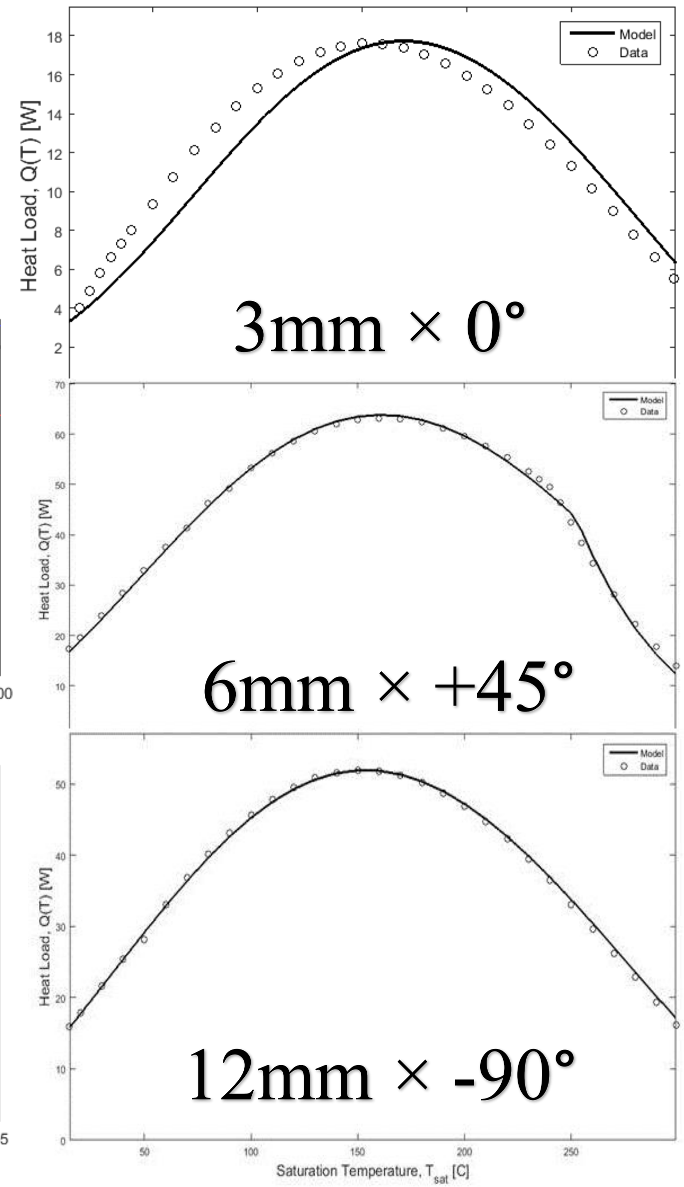






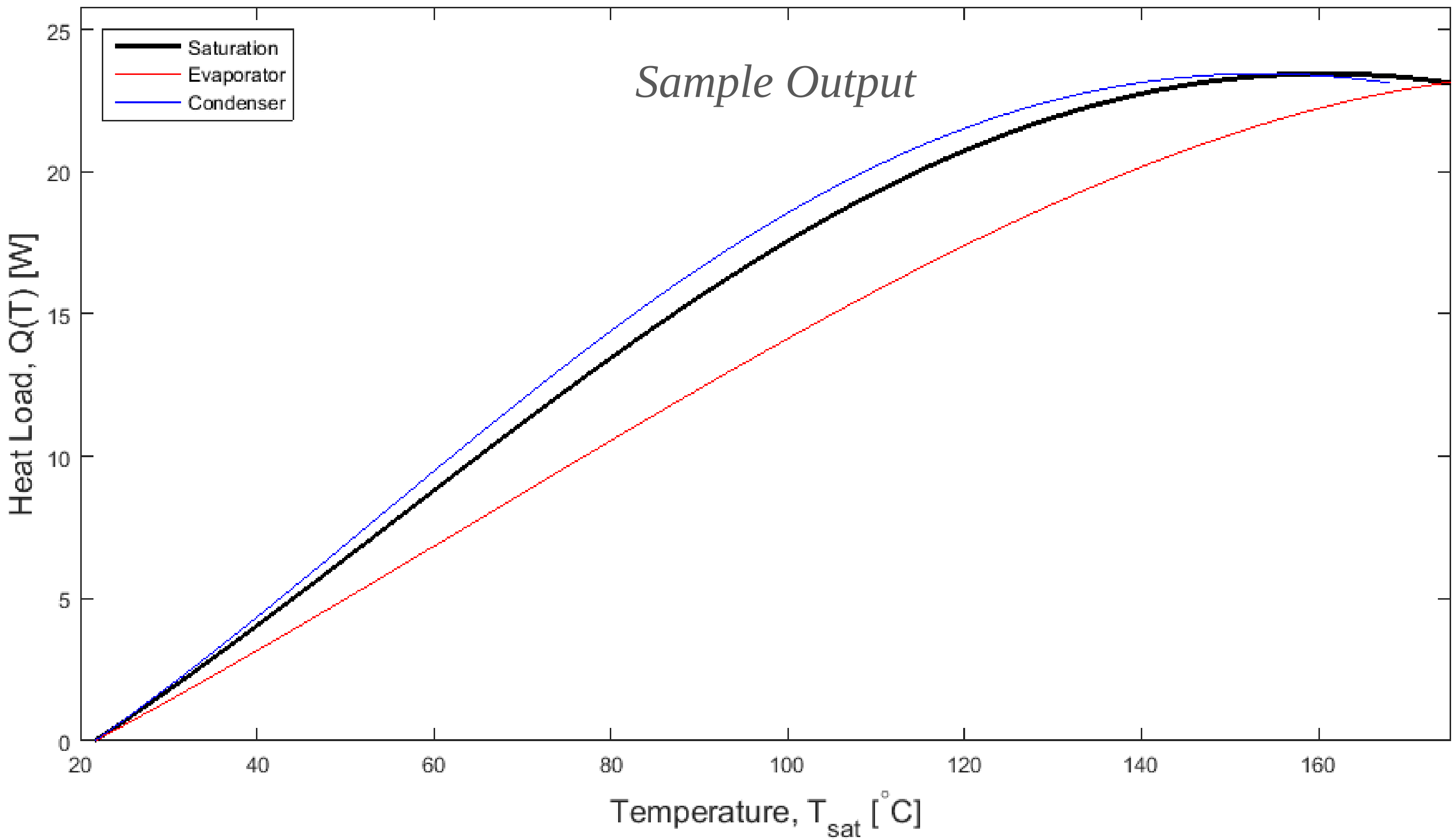


Thermacore® Data, NRL Model



Preliminary Results

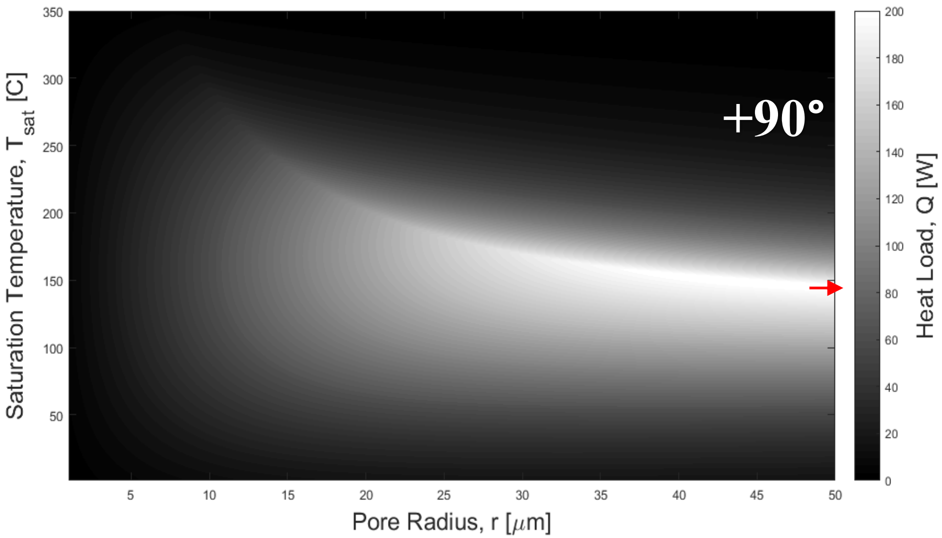
- Standard $Q(T_{sat})$ plots
  - All examples provided are for 150mm length and sintered Cu-H_2O, 25mm L_E and 50mm L_C
- Parametrically mapped contours
- Preferential operating conditions & parameter combinations
- Parameter sweeps and constrained optimization

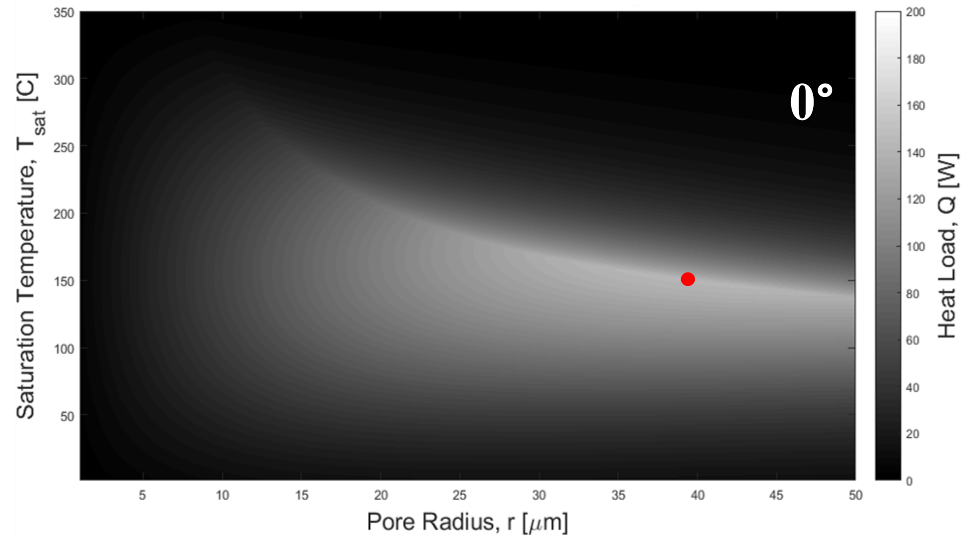


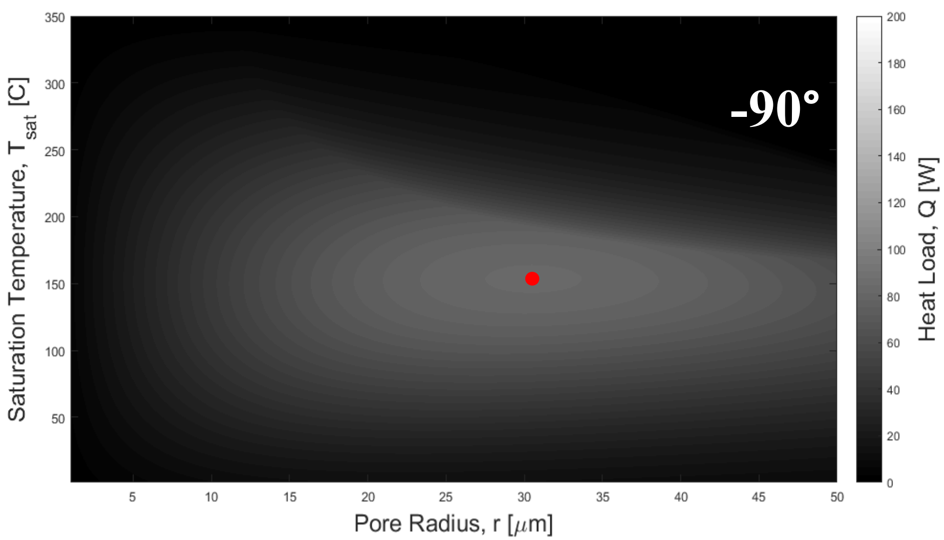
Preliminary Results

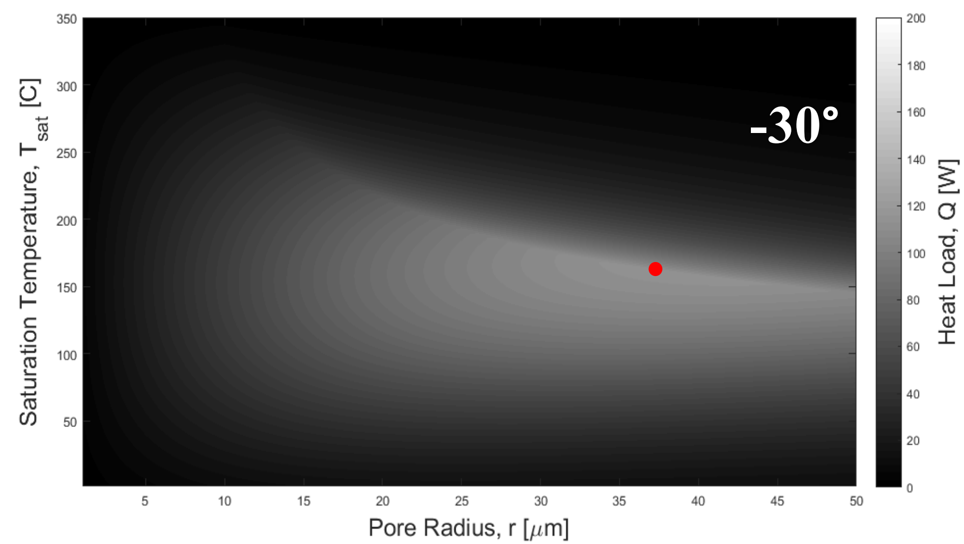
Q(r,T)

$r_{opt} = f(T,\theta)$



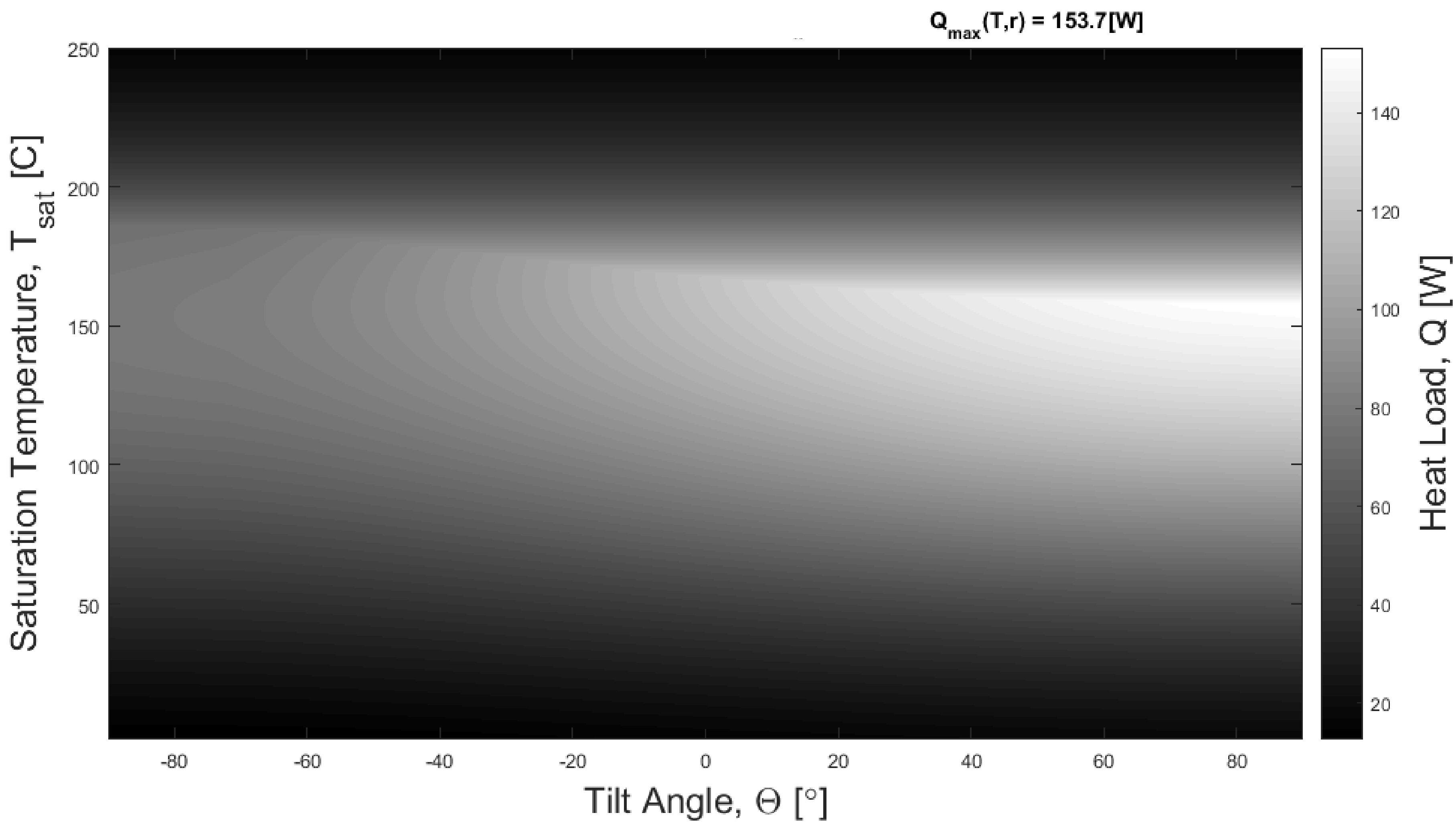






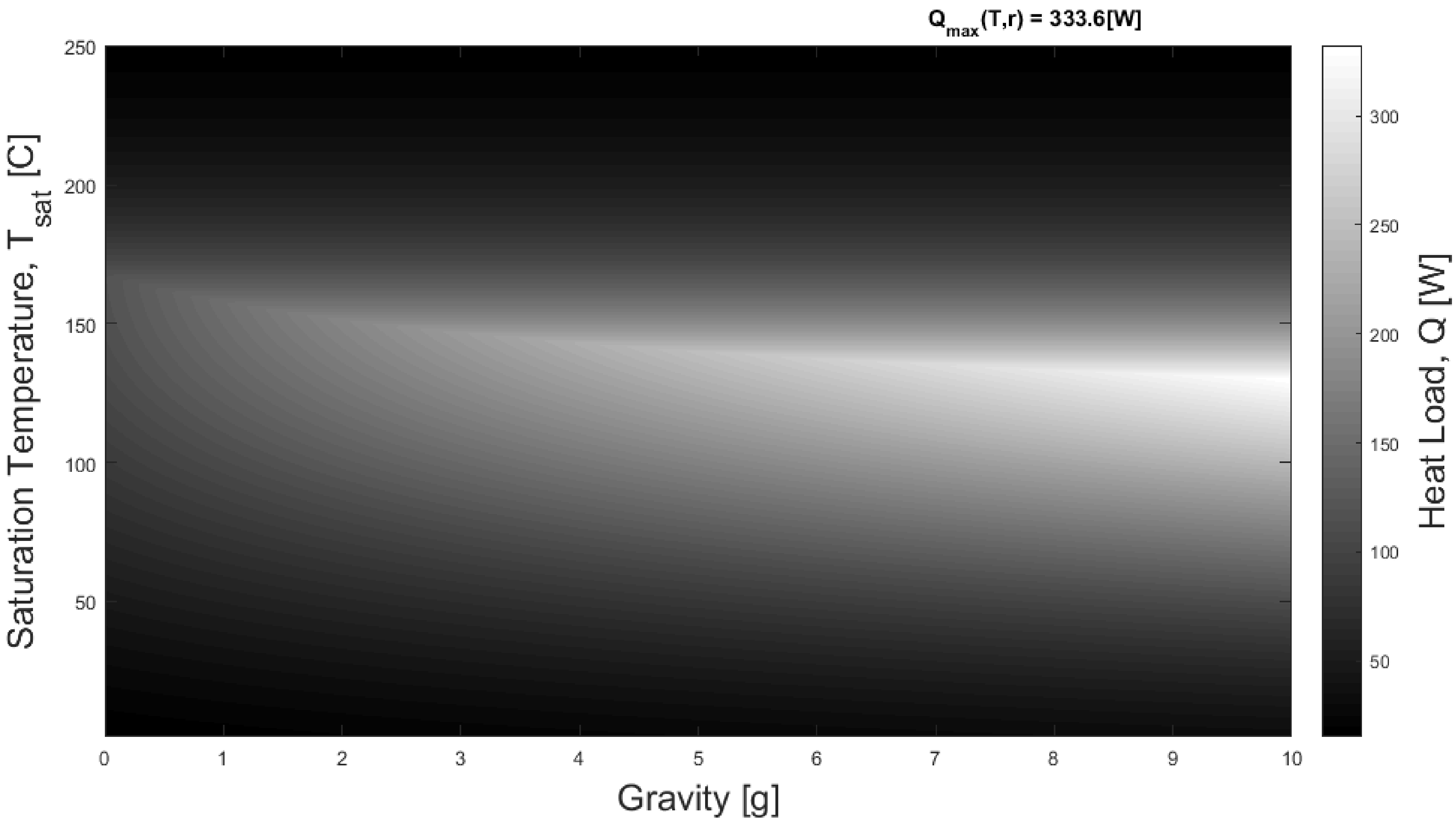
Preliminary Results

Q(θ,T)



Preliminary Results

Q(g,T)



Preliminary Results

- Dependence on load factor [g]

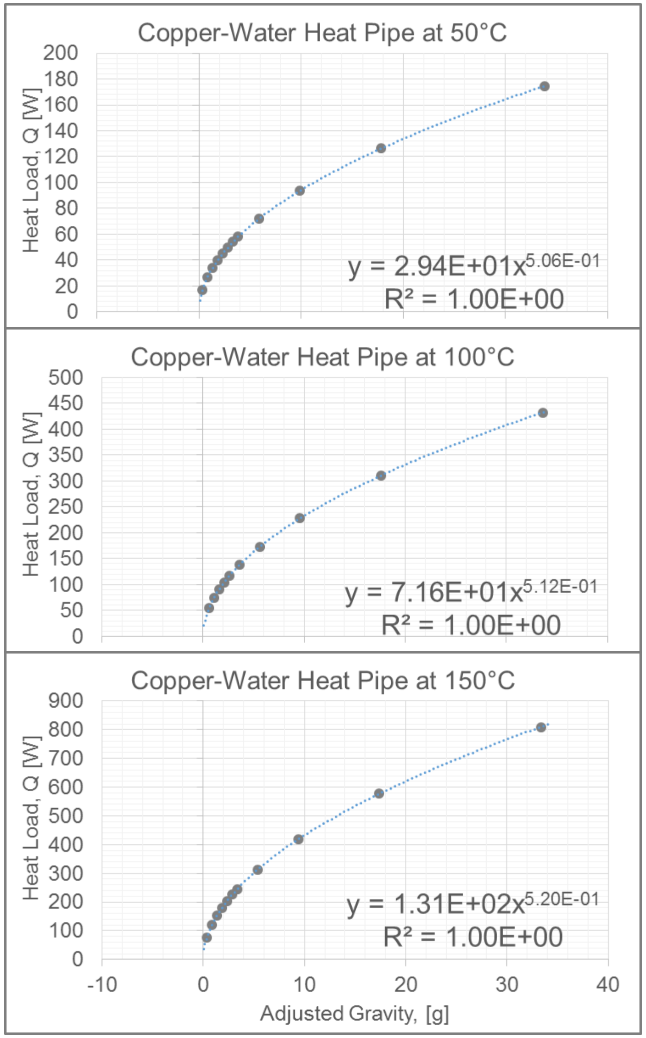
  ($g_{adjusted}$ is shifted so that Q(g=0) = 0)

  – Varies by fluid and temperature
    - Water: $Q \sim f(g'^{0.51})$
    - Ammonia: $Q \sim f(g'^{0.58})$
    - R134a: $Q \sim f(g'^{0.59})$

  ➢ *For this sample configuration*
    - *6mm OD x 150mm L, 25mm L_E, 50mm L_C*
      5% OD wick thickness

  ➢ *Could be configuration-dependent*

- Methods to increase load factor
  – Increase favorable tilt angle
    - Limited to 1 [g]
  – Increase acceleration
    - Linear: speed up / slow down
    - Centripetal: rotation rate, axial distance
      e.g. turbine blade

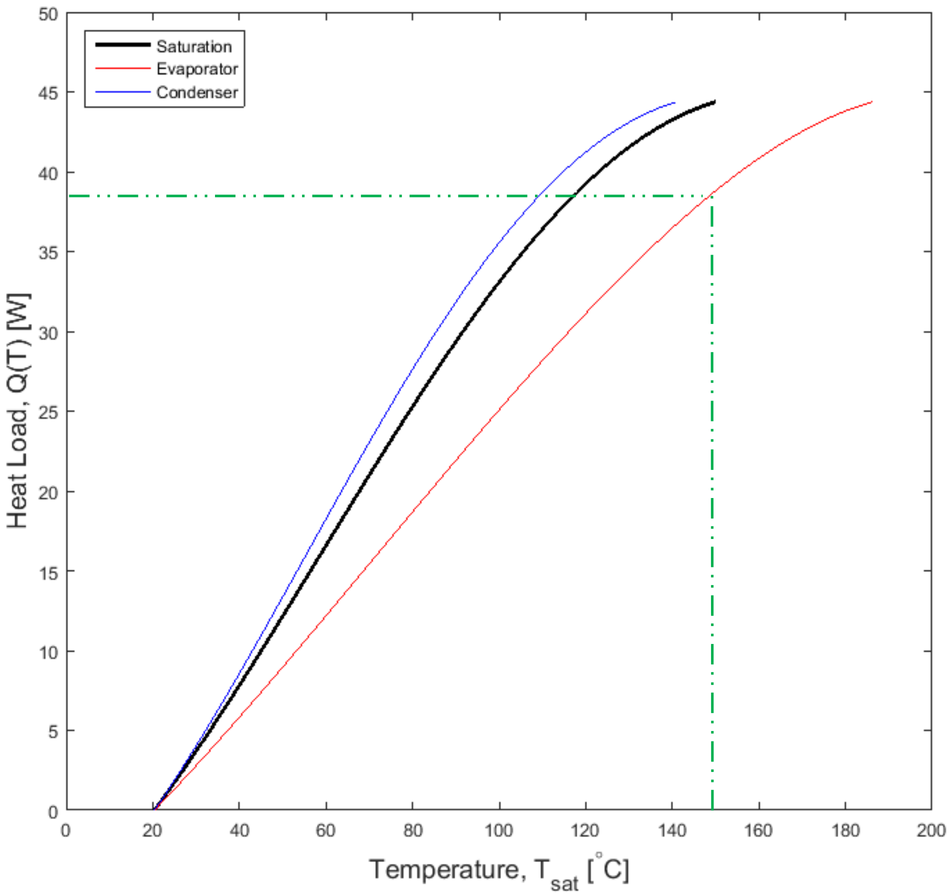


$$g_{adjusted} = g + g_{capillary}$$

Case Study

Off-The-Shelf Copper-Water Heat Pipe

- 6mm OD x 150mm Long
- 0° inclination
- 25mm evaporator
- 50mm condenser
- 0.5mm wall thickness
- 25µm pore size
- 60% porosity
- 4.7mm vapor space diameter
- k_{eff} = 5.2 kW/m/K



Optimize: Custom Heat Pipe

- ➢ Goal: maximize performance, $T_{evap} \leq 150$°C
- ➢ Must be tolerant to +/- 15° tilt
- ➢ Minimum size constraint on pore size: 25µm
- ➢ Fixed porosity, wall thickness, lengths, outer diameter, wall/wick material, fluid (water)
- ➢ Variables: pore size, vapor channel diameter

Case Study

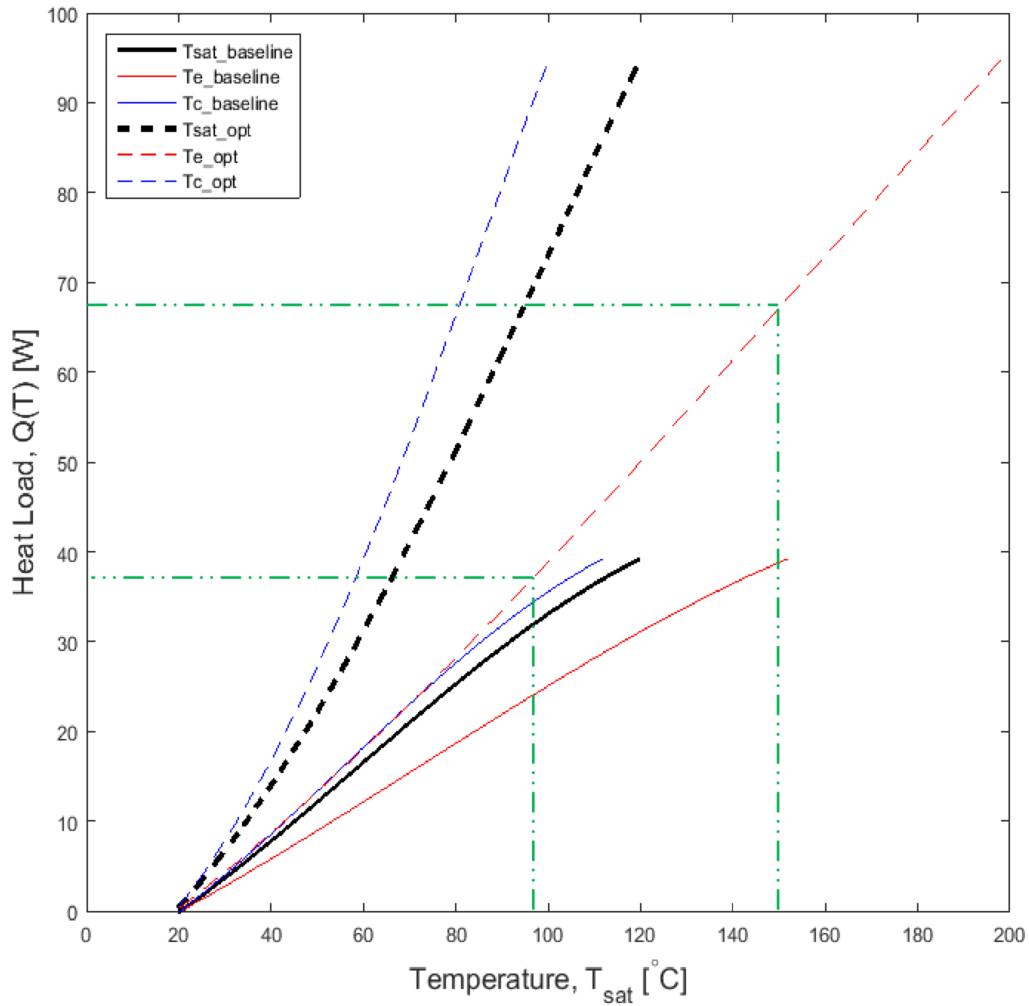
Baseline COTS Heat Pipe

- 38W at T_e = 150°C

Custom Heat Pipe

➢ Set θ = 0,-15° and maximize Q(r,d_v) subject to $T_e \leq$ 150°C

- 34µm pore size
- 3.3mm vapor space diameter
- <u>68W</u> at T_e = 150°C
  - 67W at -15°, T_e = 150°C
- 56% higher heat transfer
- k_{eff} = 5.1 kW/m/K
  - ~13x k_{Cu}
  - *Lower* than baseline case
- <u>OR</u> operate at same Q
  - T_e(Q=38W) = 97°C → **53°C cooler**



Future Work

- Consolidate into design tool & performance maps
  - Application-oriented code
- Implement time-dependent solutions
  - Derivation is time-dependent
  - These results are strictly steady state
- Experimental verification
  - Parameter optimization
  - Transient operation
- Model start-up dynamics
  - Characterize $T_{max}(t,Q)$ and Temporal Limit
- Expand to other configurations
  - Thermosyphon
  - Loop heat pipe

References

- Faghri, A., 1995, *Heat Pipe Science and Technology*, 1st ed., Taylor & Francis, Washington, D.C.
- Moody, L.F., “Friction Factors for Pipe Flow,” *Transactions of the ASME,* Vol. 66, 1944
- Munson, B.R., *et al*., *Fundamentals of Fluid Mechanics*, John Wiley & Sons, Inc., Hoboken, NJ, 2010
- Streeter, V.L., ed., *Handbook of Fluid Dynamics*, McGraw-Hill, New York, 1961
- Holman, J.P., *Heat Transfer*, 10th ed. McGraw-Hill, New York, 2010
- National Institute of Standards and Technology, NIST Chemistry WebBook, http://webbook.nist.gov/chemistry/fluid/
- Thermacore®, verification data provided with permission

Acknowledgements

- US Naval Research Laboratory
- TTH Research, Inc.
- Thermacore, Inc.